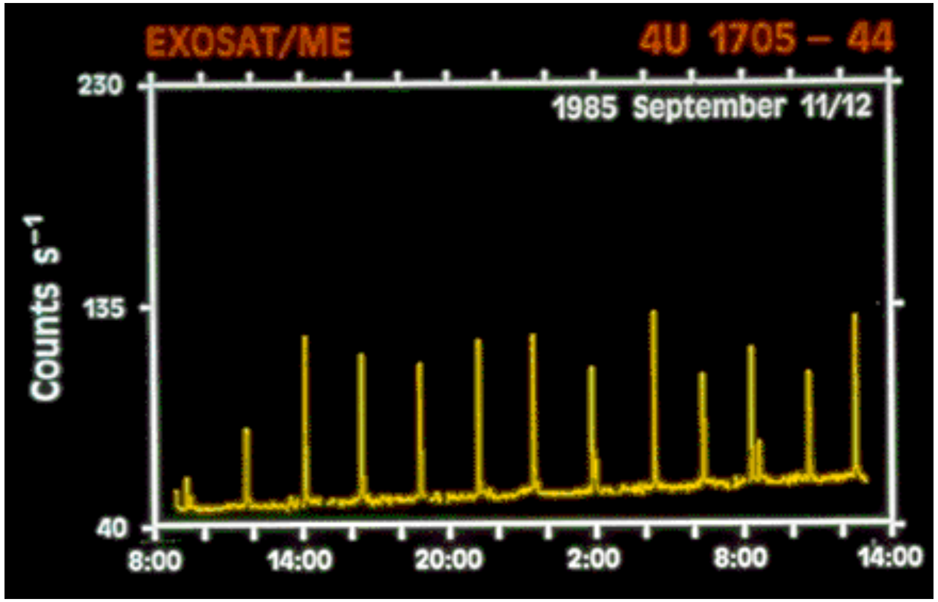
Determining neutron star parameters from cooling phases of X-ray bursts

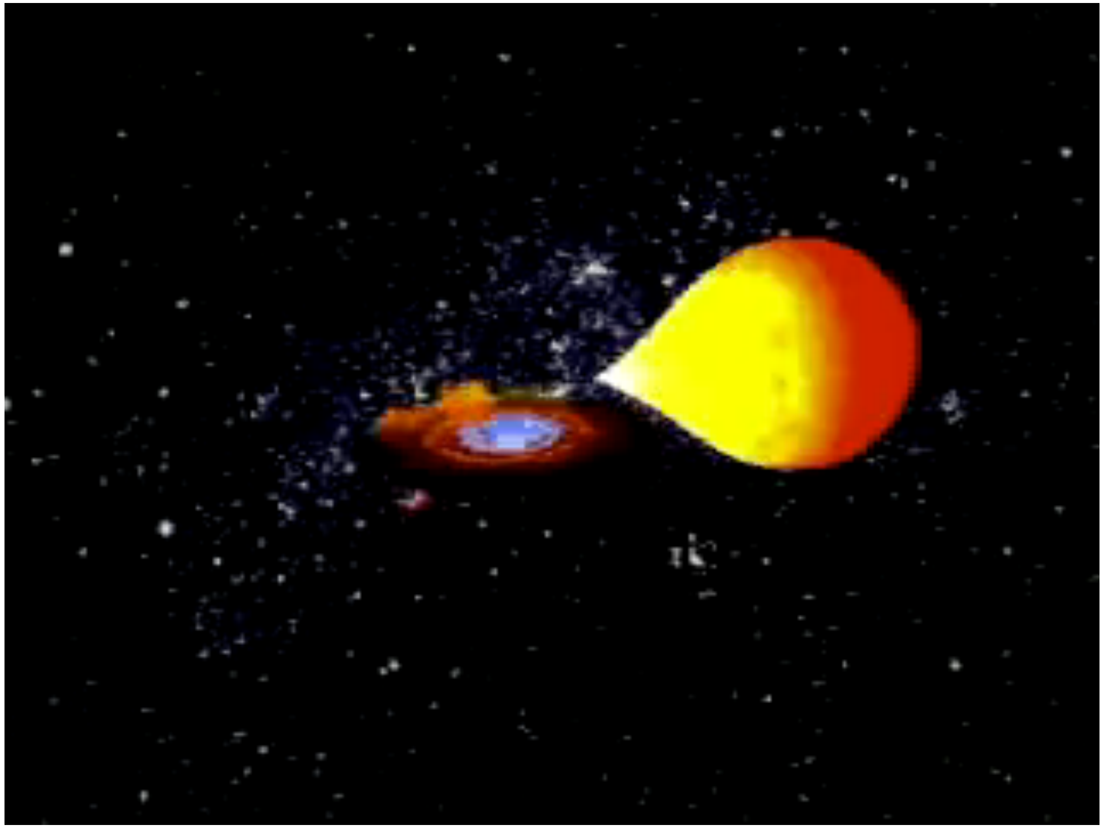
Juri Poutanen (University of Turku, Finland)

Collaborators:
Valery Suleimanov, Klaus Werner (Univ. Tübingen, Germany)
Joonas Nättilä (Univ. Turku, Finland)
Andrew Steiner (Univ. Tennessee & Oak Ridge National Lab, USA)
Jari Kajava, Erik Kuulkers (ESAC, Spain)
Duncan Galloway (Monash Univ., Australia)

X-ray bursts

1. Discovered in the middle of 1970s (e.g. Grindlay et al. 1976).
2. Last for 10-1000 s. Sometimes reach Eddington limit.
3. Originate from accreting neutron stars in low-mass binary systems (LMXBs). About 70 known.
4. Thermonuclear unstable burning of H and He (and maybe C) accreted from the companion in the surface layers of neutron stars.





Rossi X-ray Timing Explorer

Operated for 16 years:
from 30 Dec , 1995
to 3 Jan, 2012

Main instrument:
Proportional Counter Array,
2.5-60 keV

Observed >2000 X-ray bursts

Plan

- Determining neutron star mass-radius (M-R) from thermal spectra
- Neutron star atmosphere models
- X-ray bursts: dependence on the accretion state
- Constraining neutron star M-R and EoS with the cooling tail method.

Easy to understand - hard to do: direct spectral fitting with the atmosphere models

Computationally expensive

Hard to understand - easy to do: spectral fitting of the data and the models with the blackbody

Computationally cheap and fast

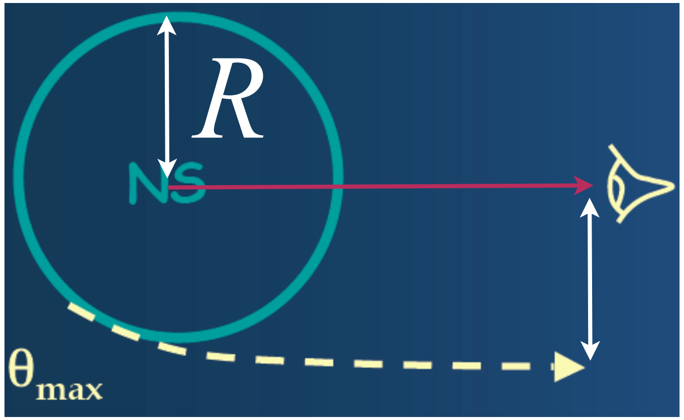
Neutron star mass-radius relation using blackbody radius at "infinity"

Fitting the bursts spectra with the blackbody we get the temperature T_{bb} and normalization K

$$F_{bol} = \sigma_{SB} T_{bb}^4 K, \quad K = \frac{R_{bb}^2}{D^2}$$

If the distance is known, we can determine apparent radius, which is related to R and M of the neutron star.

$$R_{bb} = R_\infty = R(1+z) = R(1 - R_S / R)^{-1/2}$$



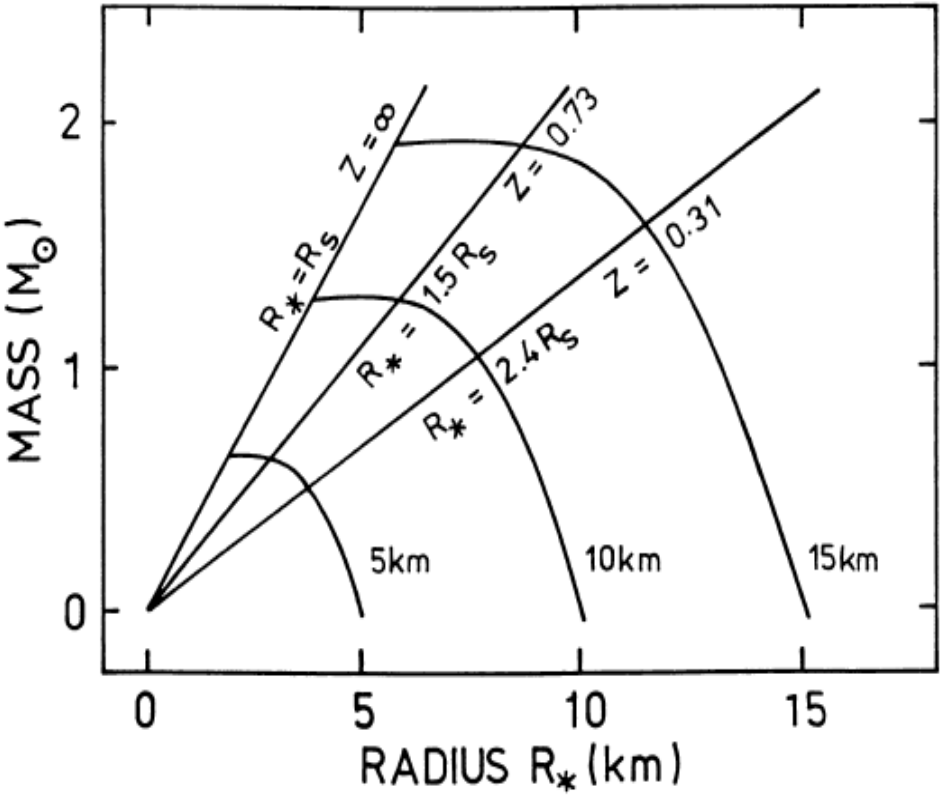
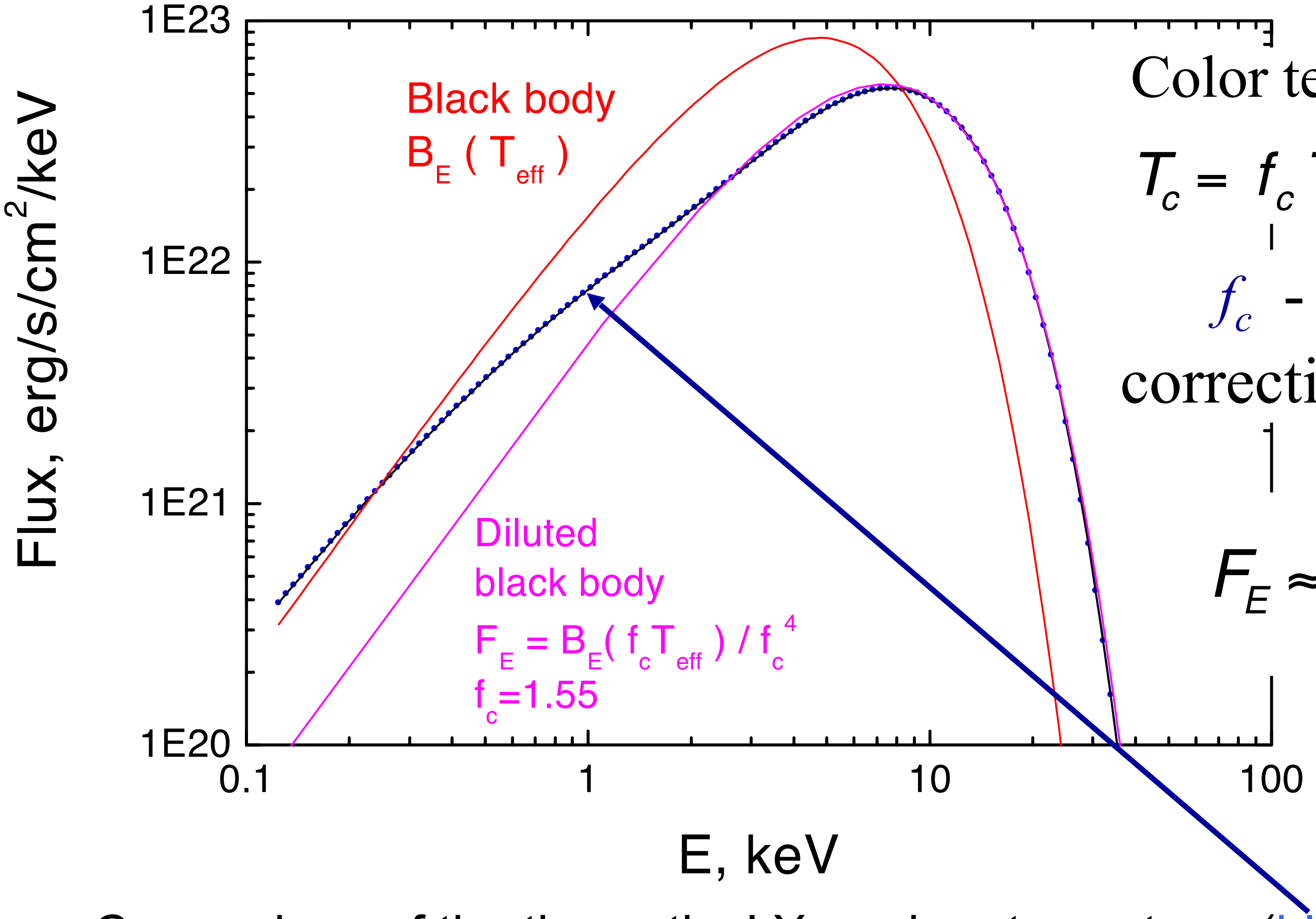


Fig. 4.3. Mass-radius relation for three hypothetical values of the blackbody radius R_∞ (5, 10, and 15 km). For clarity, we have not indicated error regions resulting from the uncertainties in the measurements. The straight lines indicate radii R_*, equal to the Schwarzschild radius R_S, 1.5 R_S, and 2.4 R_S (in the text we use R_g instead of R_S). The latter could, for example, result from an analysis of a burst with radius expansion (see text), or from the determination of the gravitational redshift of an observed spectral feature. For a given mass, the observed blackbody radius, R_∞, has a minimum value $(1.5\sqrt{3})\,R_g$; conversely, for a given blackbody radius R_∞ the mass cannot be larger than R_∞ (km)/7.7 $M_\odot$.

Spectrum from NS atmosphere



Color temperature

$$T_c = f_c\, T_{eff}$$

f_c - color correction factor

$$F_E \approx \frac{1}{f_c^4} B_E\left(f_c T_{\rm eff}\right)$$

Comparison of the theoretical X-ray burst spectrum (blue curve) with the black body (red) of the same effective temperature.

Neutron star mass-radius relation using blackbody radius at "infinity"

$$F = \sigma T_{bb}^4 \left(\frac{R_{bb}}{D} \right)^2 = \sigma T_{eff,\infty}^4 \left(\frac{R_\infty}{D} \right)^2$$

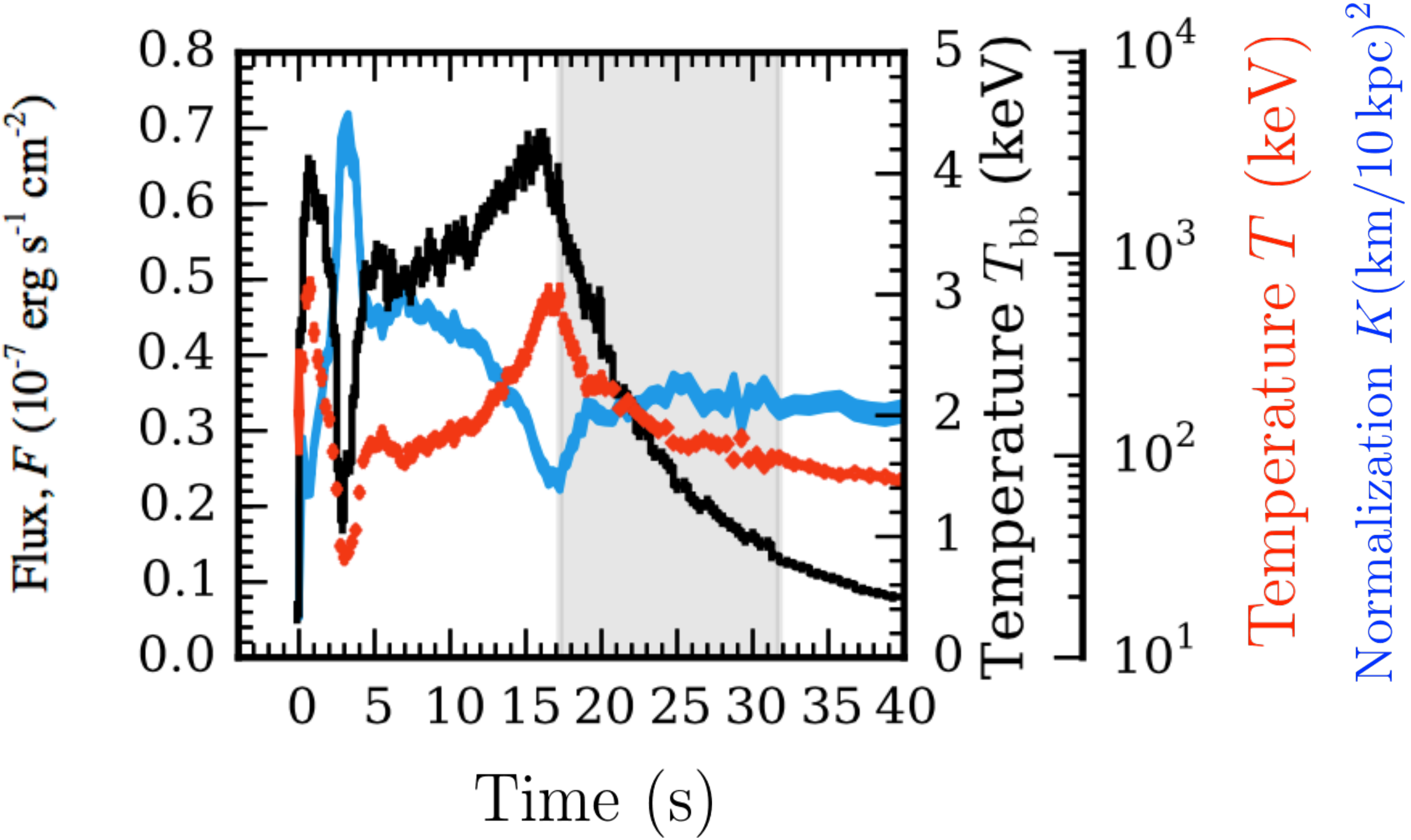
$$f_c = T_{bb} / T_{eff,\infty}$$

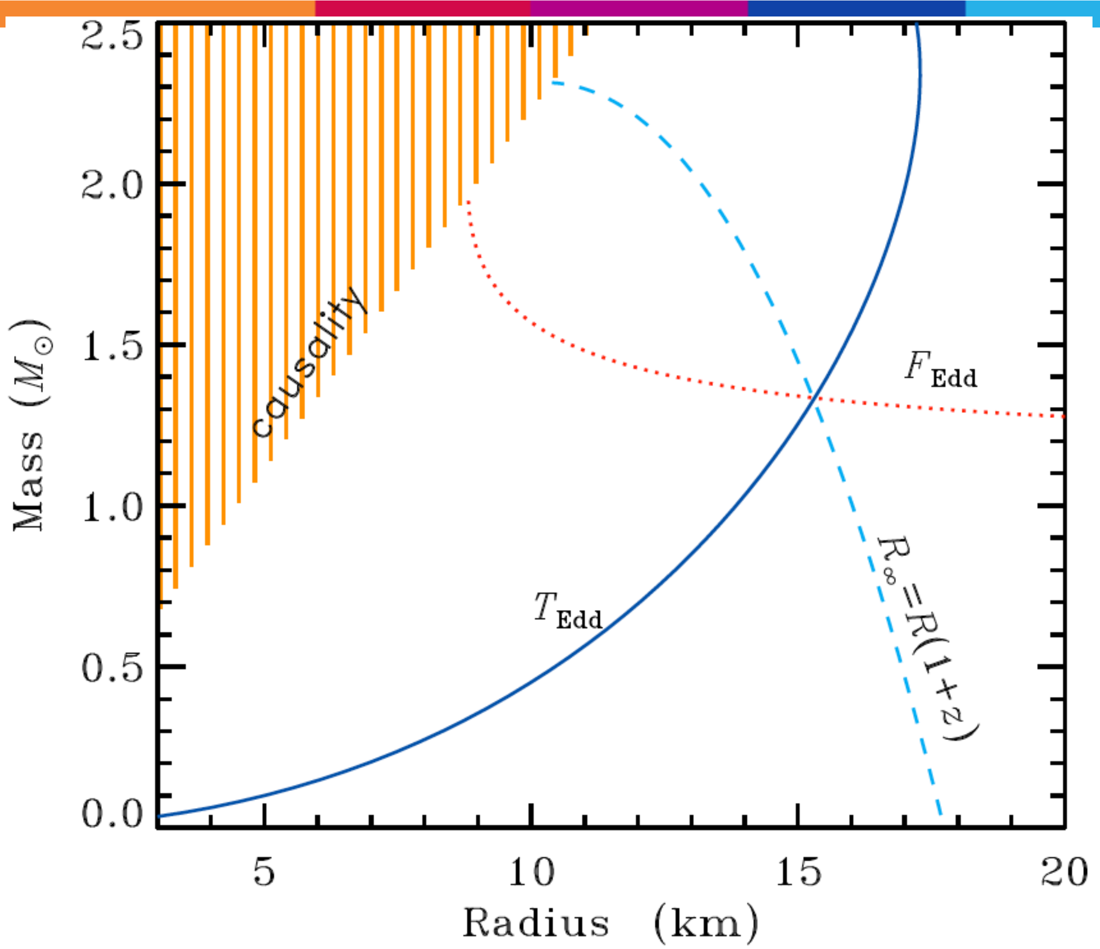
$$K = (R_{bb}/D)^2$$

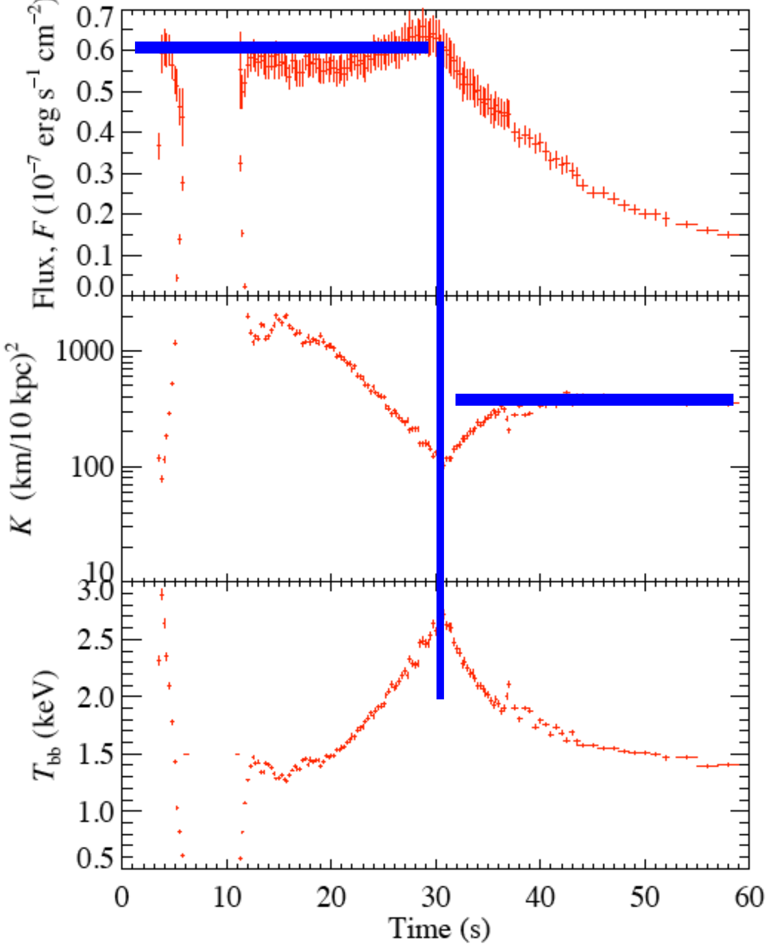
$$R_\infty = R_{bb} f_c^2 = D_{10} \sqrt{K} f_c^2$$

$$D_{10} = D / 10\mathrm{kpc}$$

Photospheric Radius Expansion X-ray bursts







$$F_{\rm Edd} = \frac{L_{\rm Edd}}{4\pi D^2} = \frac{GMc}{D^2 \kappa_{\rm e}(1+z)}$$

$$R_\infty = R_{bb} f_c^2 = D_{10}\sqrt{K} f_c^2$$

Distance-independent measure

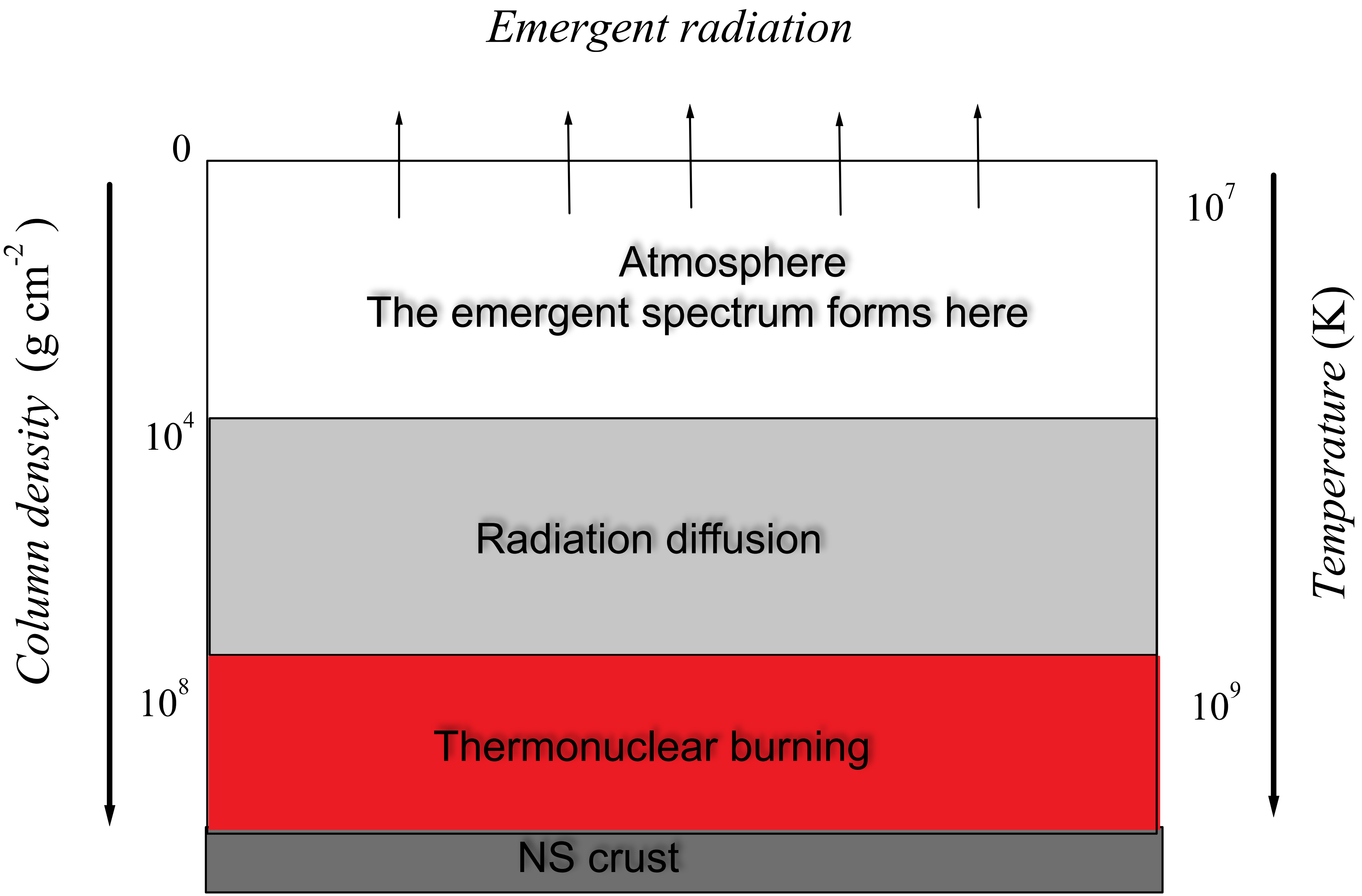
$$A = (R_\infty / D_{10})^{-1/2} = K^{-1/4}/f_c$$

$$T_{\rm Edd,\infty} = \left(\frac{gc}{\sigma_{\rm SB}\kappa_{\rm e}}\right)^{1/4} \frac{1}{1+z} = 6.4 \times 10^9\, A\, F_{\rm Edd}^{1/4}\, {\rm K}$$

What bursts can be used?

We have to be sure that spectral evolution during the cooling tail follows theoretical predictions for a passively cooling atmosphere.

Plane parallel atmosphere model of the burning layer



Emergent radiation

0

10^4

10^8

Column density (g cm^{-2})

10^7

10^9

Temperature (K)

Atmosphere
The emergent spectrum forms here

Radiation diffusion

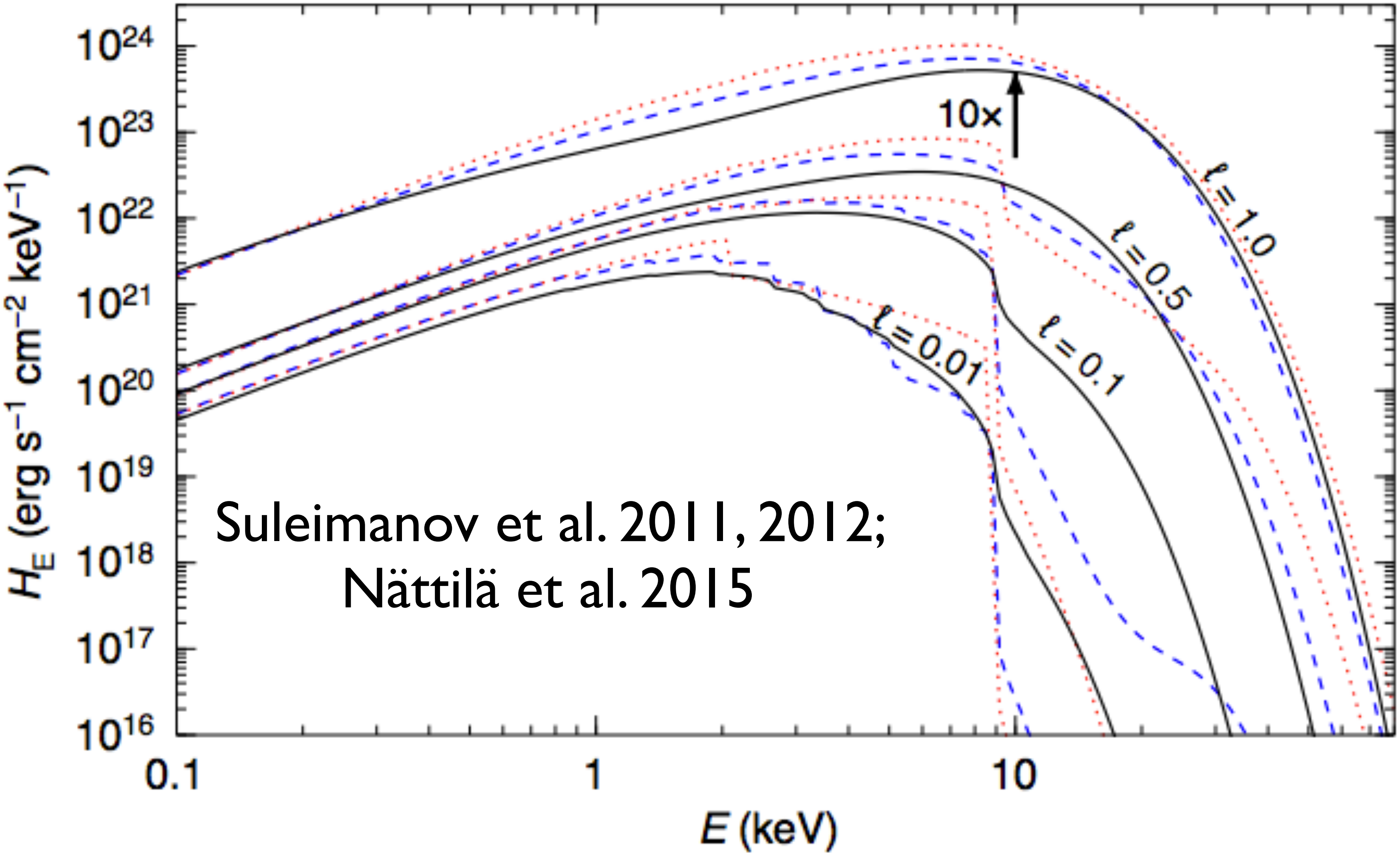
Thermonuclear burning

NS crust

Atmosphere models

$\frac{\mathrm{d}P_{\mathrm{g}}}{\mathrm{d}m} = g - g_{\mathrm{rad}}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$	Hydrostatic equilibrium
$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$	Radiative transfer
$\sigma(x,\mu) = \kappa_{\mathrm{e}} \frac{1}{x} \int_0^\infty x_1 \mathrm{d}x_1 \int_{-1}^{1} \mathrm{d}\mu_1 R(x_1,\mu_1;x,\mu) \left(1 + \frac{C\,I(x_1,\mu_1)}{x_1^3}\right),$	Electron opacity
$\int_0^\infty \mathrm{d}x \int_{-1}^{+1} [\sigma(x,\mu) + k(x)]\,[I(x,\mu) - S(x,\mu)]\ \mathrm{d}\mu = 0,$	Energy balance
$P_{\mathrm{g}} = N_{\mathrm{tot}}\, kT,$	Ideal gas law

Atmosphere models: emerging spectrum

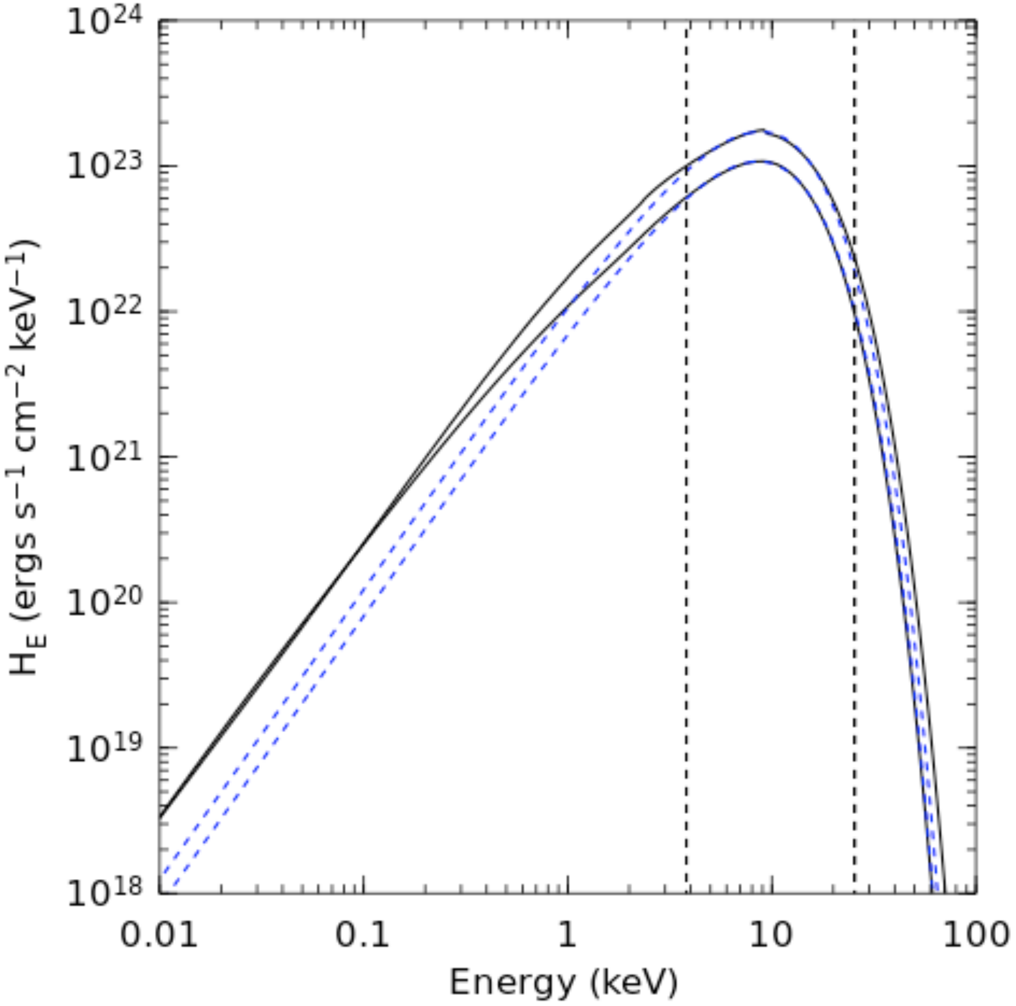


Suleimanov et al. 2011, 2012;
Nättilä et al. 2015

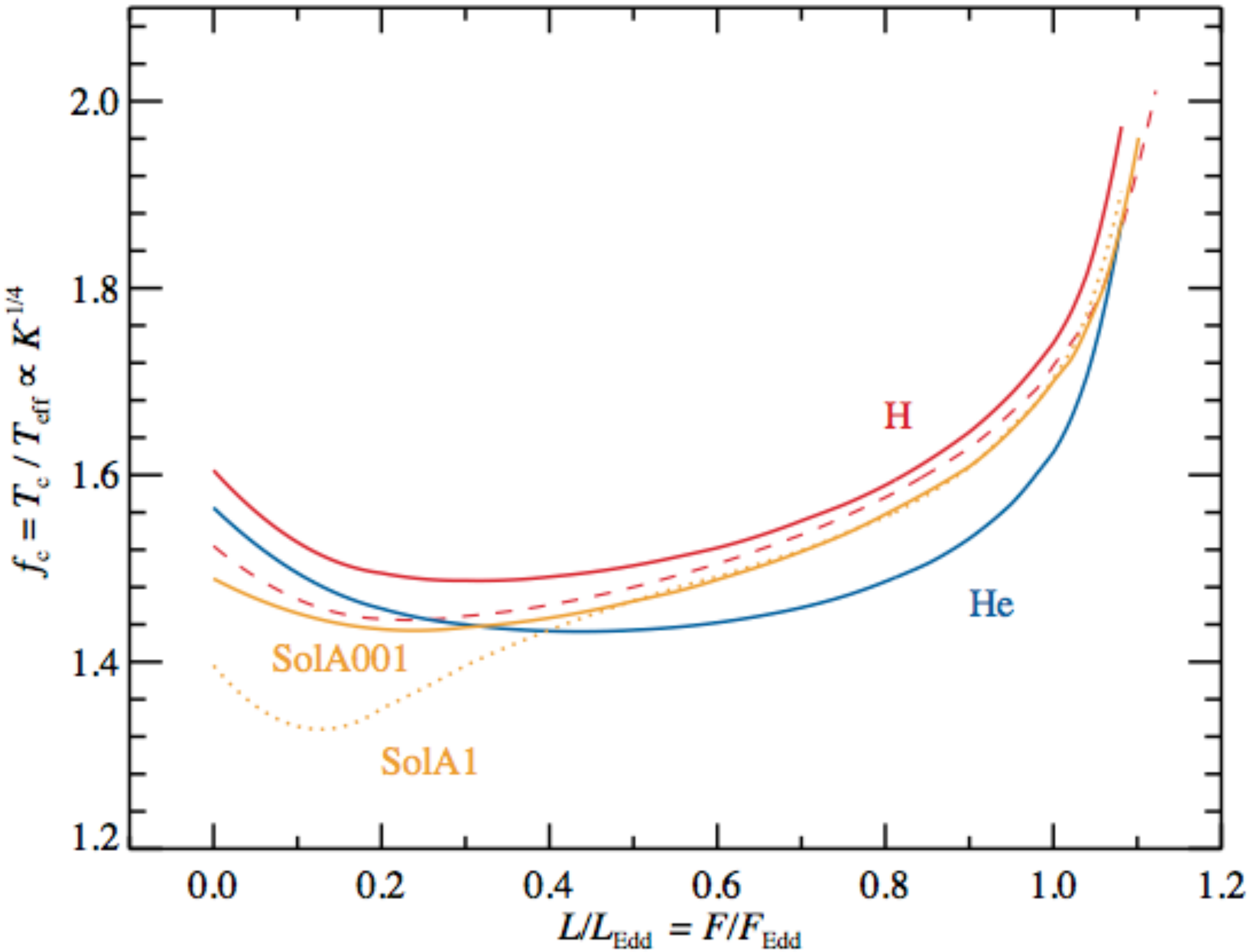
Atmosphere models: emerging spectrum

Usually described well by diluted black body (in range 2.5 - 25.0 keV)

$$F_E = \frac{1}{f_c^4} B_E(T_c = f_c T_{\rm eff})$$



Color-correction factor f_c



Color-correction factor f_c

- Models: $$F_E = \frac{\pi}{f_\mathrm{c}^4} B(f_\mathrm{c} T_\mathrm{eff})$$
- Observations: $$F_E = \pi K_\mathrm{bb} B(T_\mathrm{bb})$$

$$\Rightarrow \quad f_\mathrm{c} \propto K_\mathrm{bb}^{-1/4}$$

$$T_\mathrm{bb} \propto f_\mathrm{c} T_\mathrm{eff}$$

Data vs. models

- Models are well described by a simple blackbody (with *T* correction)
- Observations of the cooling are well described by a simple blackbody

⇒ We can simplify and only compare the temperature correction!

The cooling tail method

$$K = \left(\frac{R_{bb}}{D_{10}}\right)^2 = \frac{1}{f_c^4}\left(\frac{R_\infty}{D_{10}}\right)^2 \longrightarrow \boxed{K^{-1/4} = A\, f_c(F \,/\, F_{\mathrm{Edd}})}$$

$$A = (R_\infty[\mathrm{km}]/D_{10})^{-1/2}$$

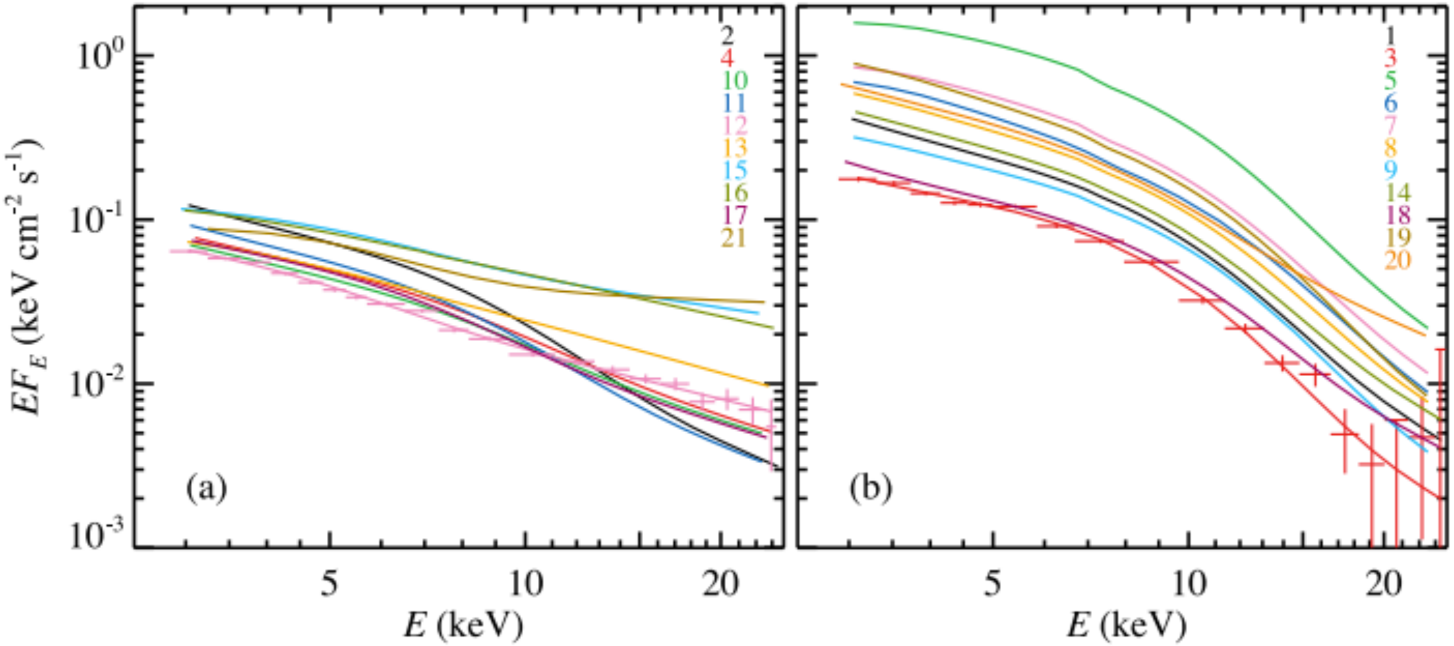
The observed evolution of $K^{-1/4}$ vs. F should look similar to the theoretical relation f_c vs. F/F_{Edd}

Two free parameters: A and F_{Edd}.

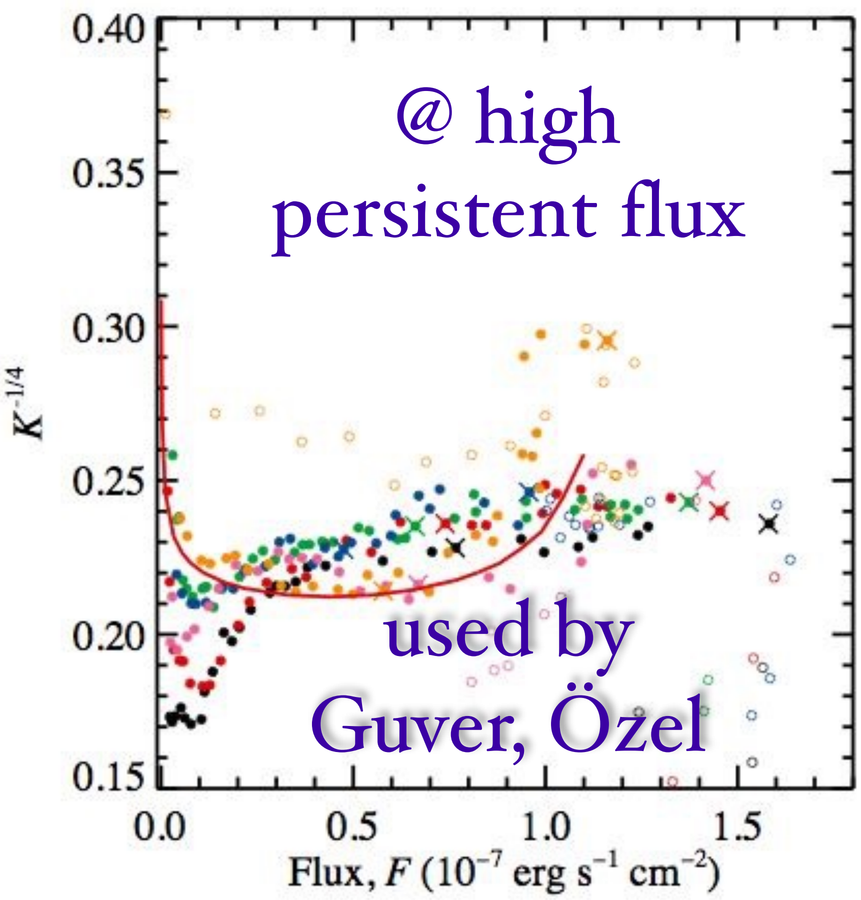
The data

Photospheric Radius Expansion bursts

- Roughly 2 kinds of bursts
  - Hard state bursts (with low accretion)
  - Soft state bursts (with high accretion)

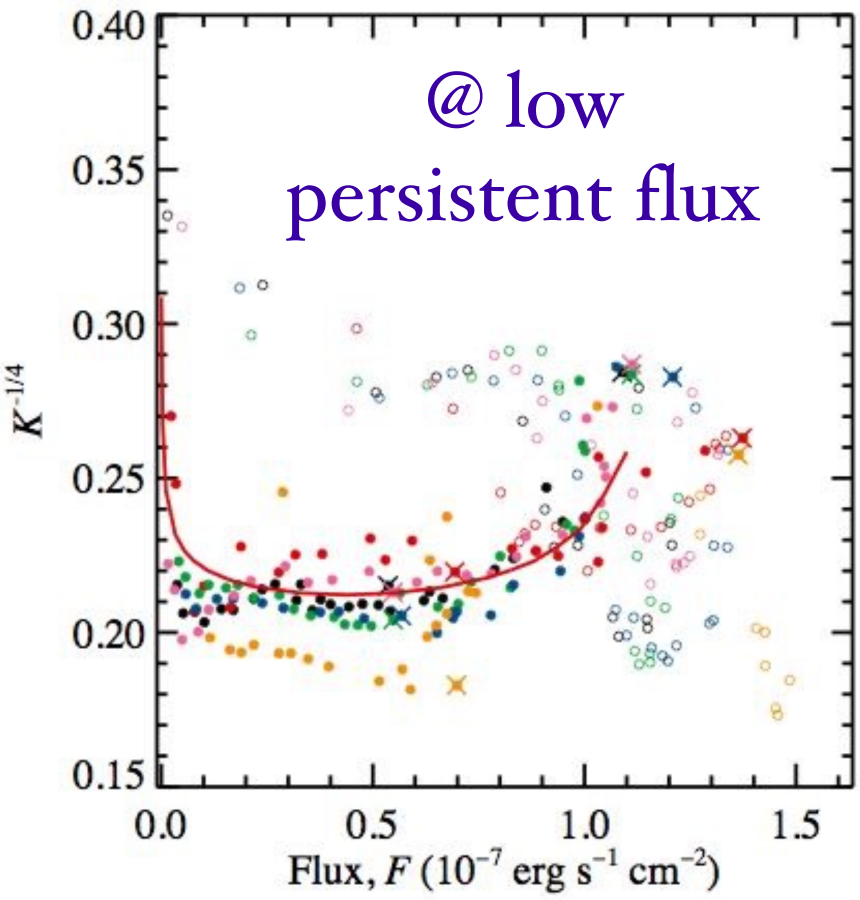


Bursts from 4U 1608-52 at different accretion rates



@ high persistent flux

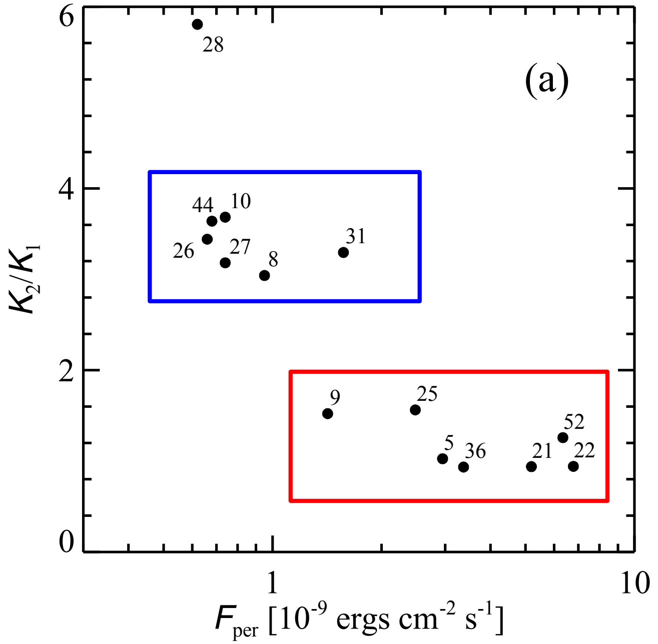
used by Guver, Özel



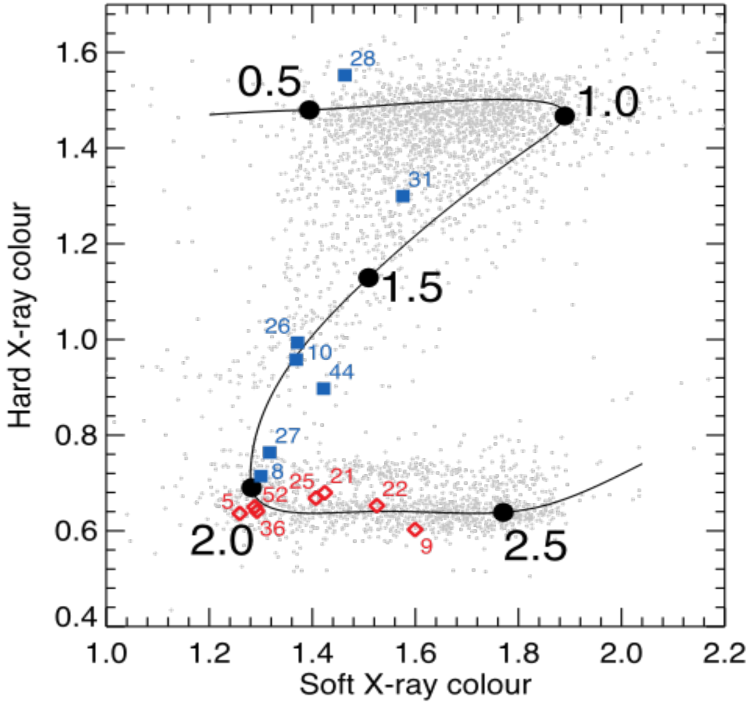
@ low persistent flux

Poutanen et al. (2014)

Ratio of bb normalizations at =1/2 touchdown flux and at the touchdown



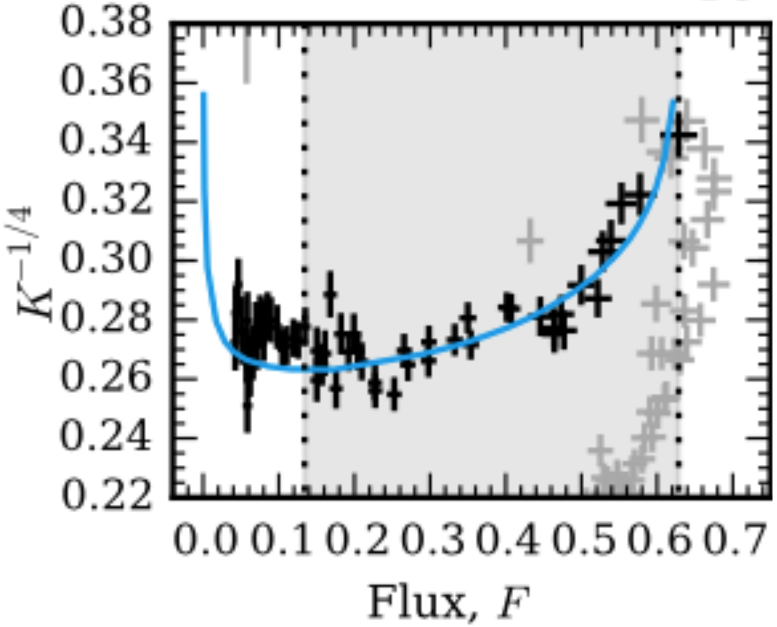
4U 1608-52

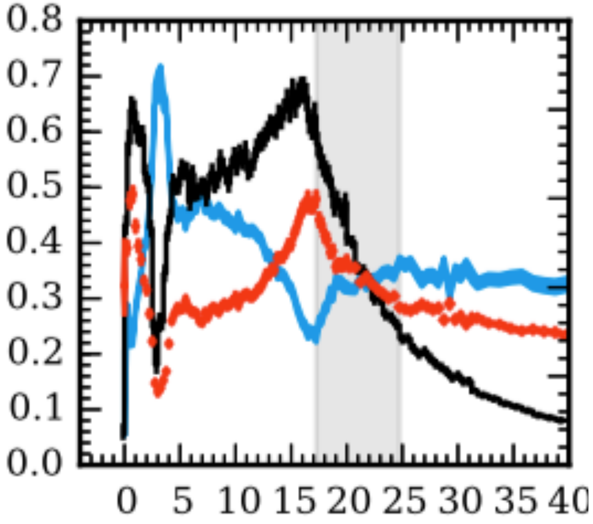


Evolution of blackbody normalization depends strongly on persistent flux and on the position on the color-color diagram

4U 1724-307

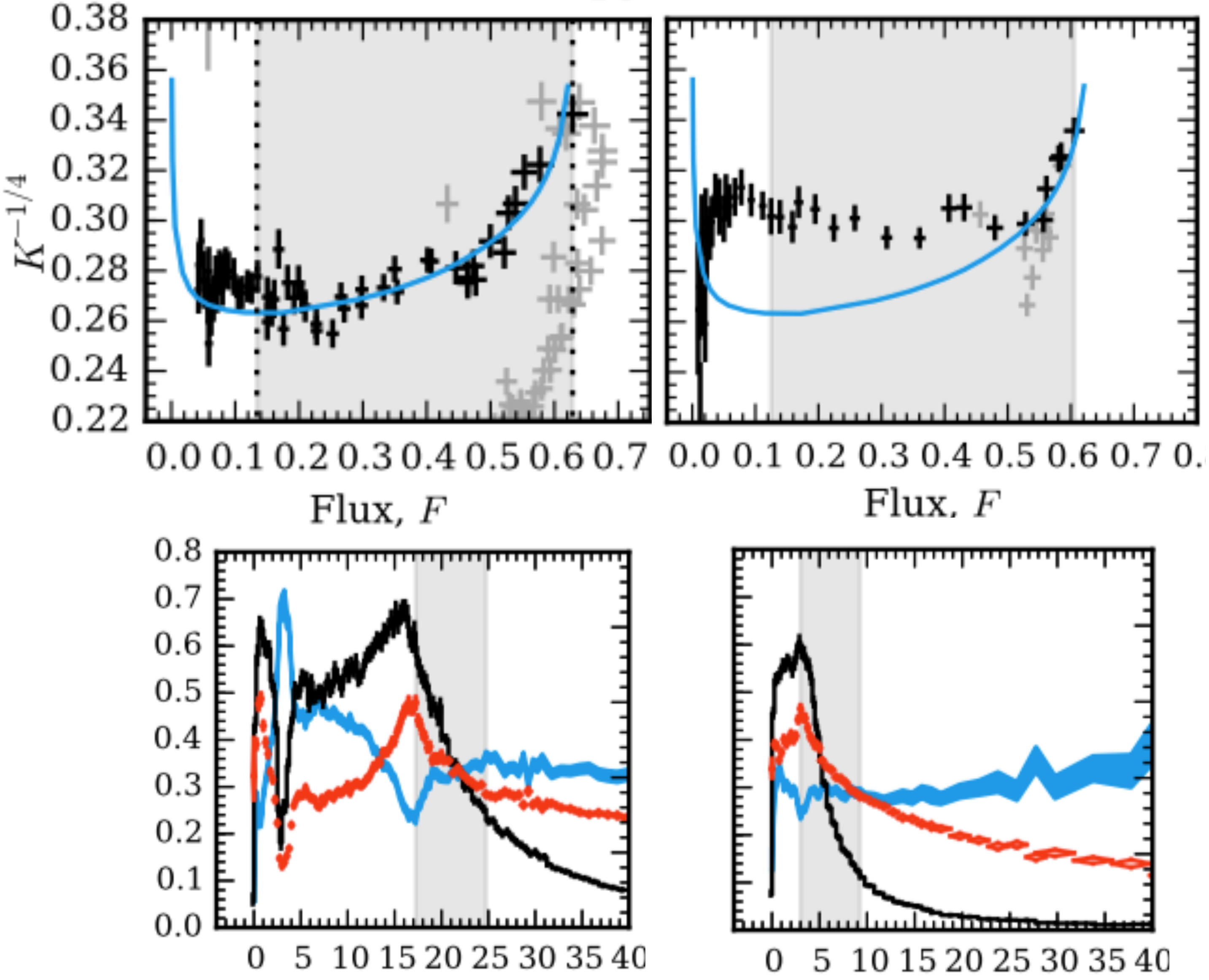
Hard state





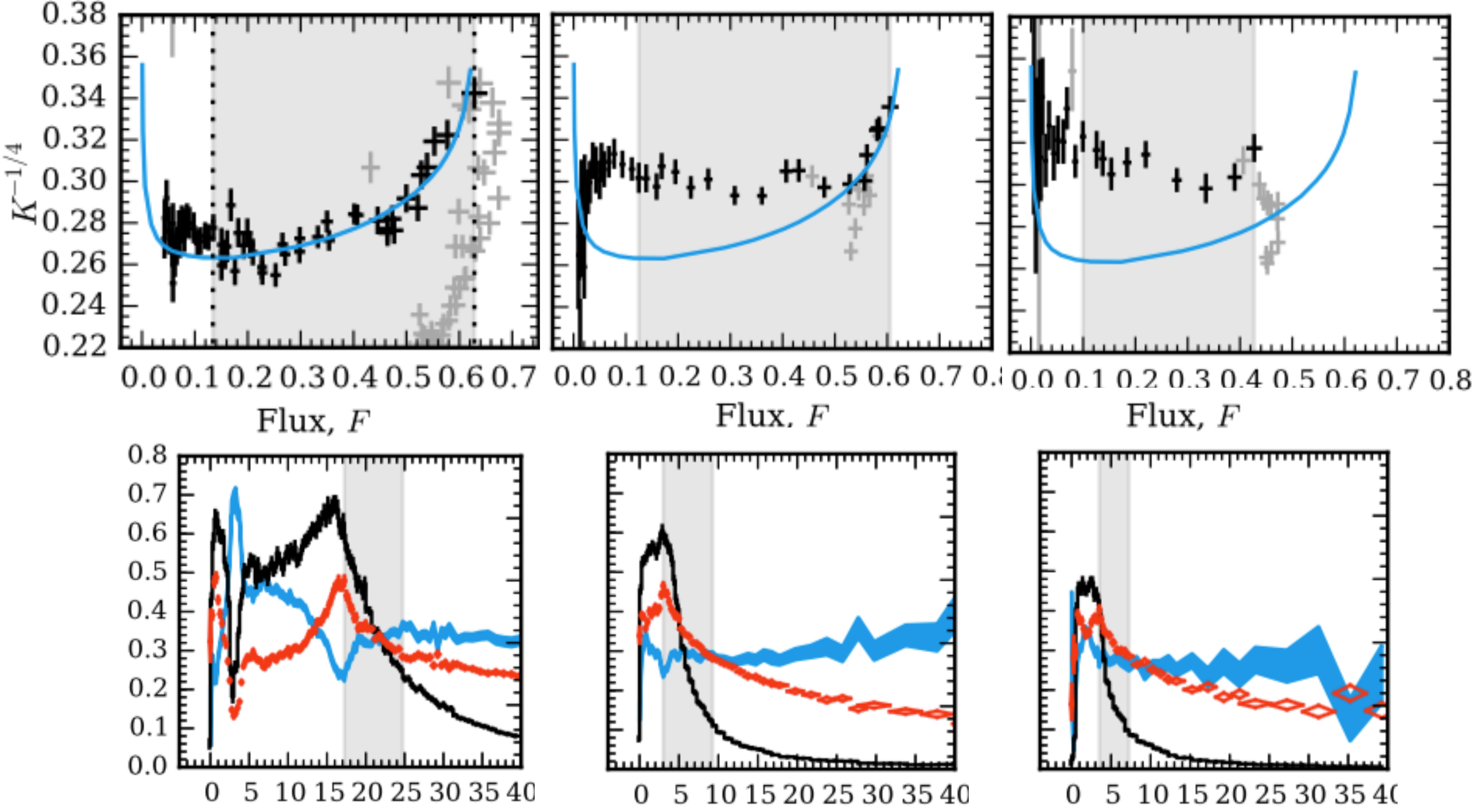
4U 1724-307

Hard state **Intermediate state**



4U 1724-307

Hard state Intermediate state Soft state



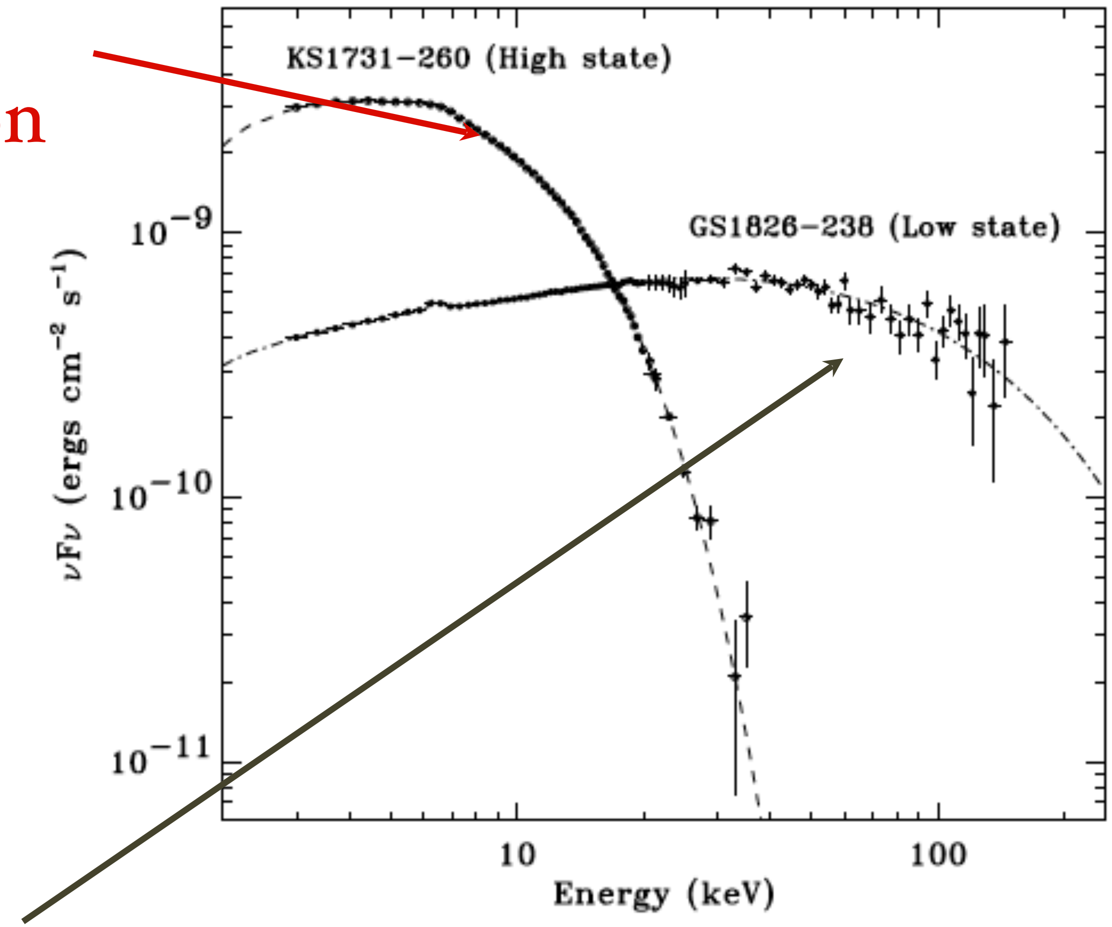
Why the apparent area is different in different bursts?

Why the apparent area is different in different bursts?

Influence of accretion on the burst apparent area and the spectra

Two states of LMXB

Soft/high state -
optically thick, cool region

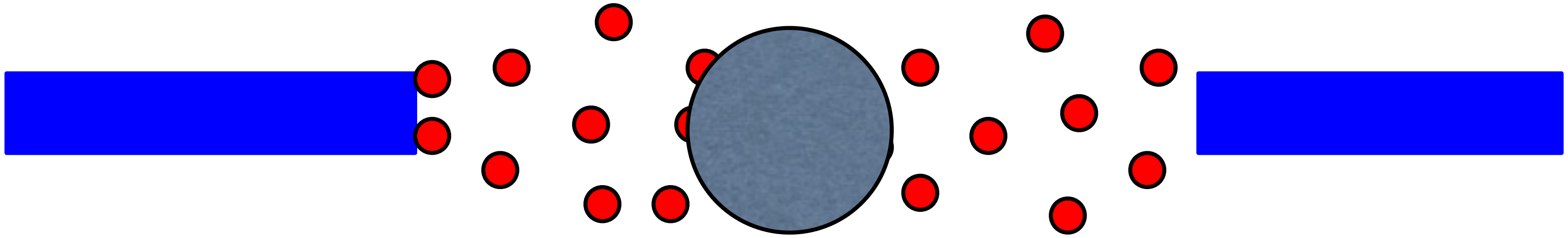


Barret et al. 2000

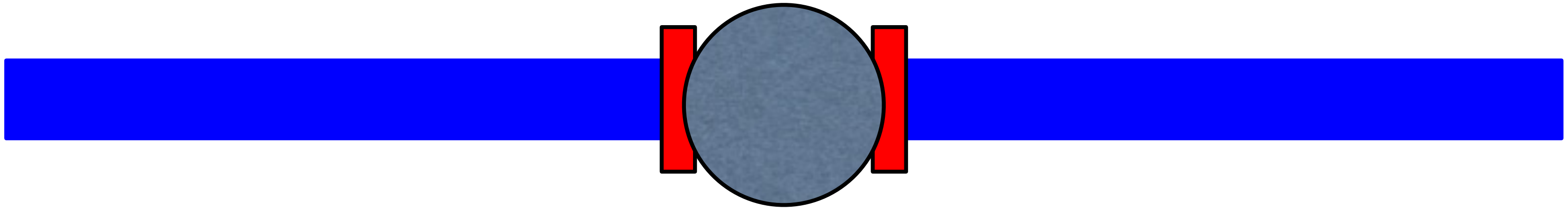
Hard/low state -
optically thin, hot region

Accretion geometry

Hard state - hot flow / hot optically thin boundary layer

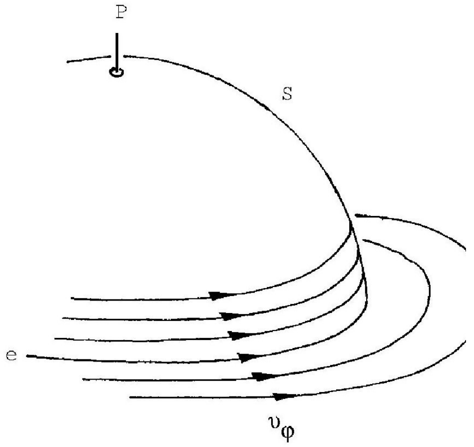


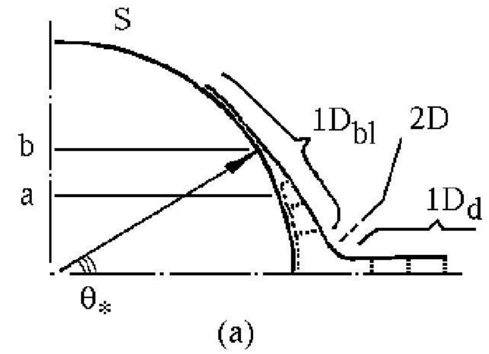
Soft state - optically thick boundary layer



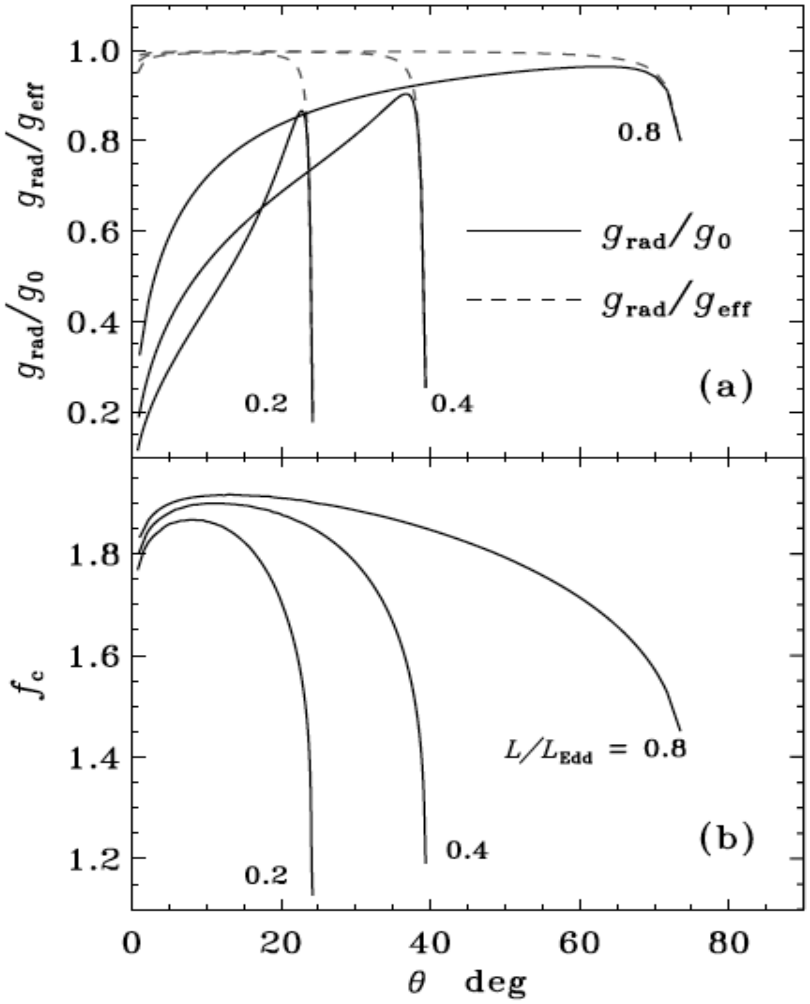
1. Accretion disk can blocks nearly 1/2 of the star.
2. Spreading of matter on NS surface affects the atmosphere structure increasing f_c

Inogamov & Sunyaev (1999)





Suleimanov & Poutanen (2006)

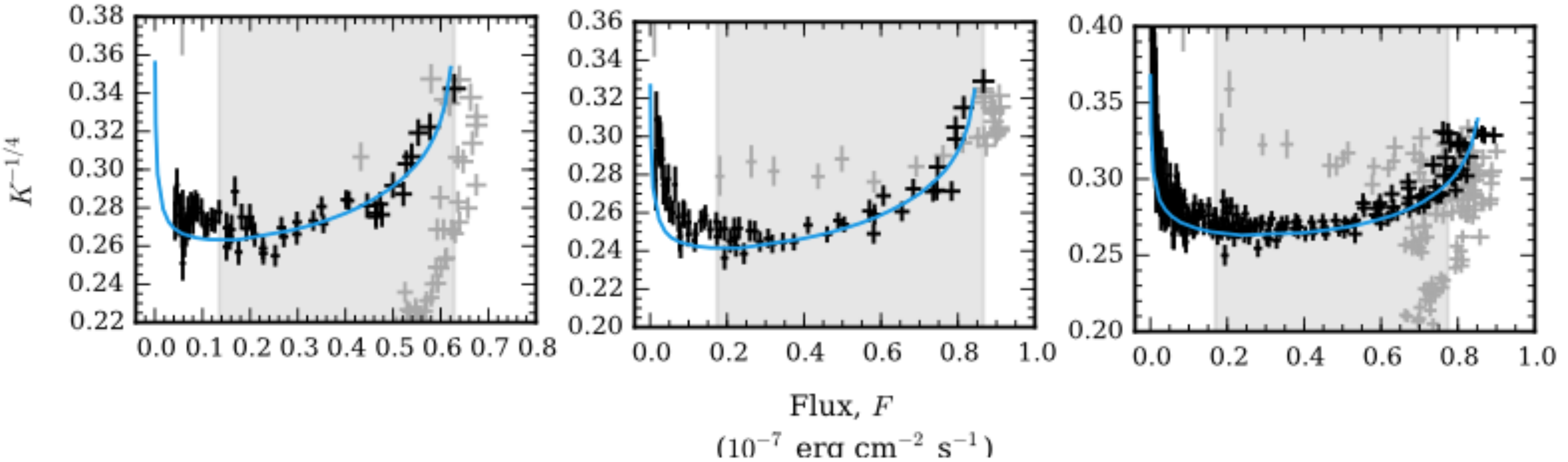


radiative acceleration/ gravitational
radiative / effective

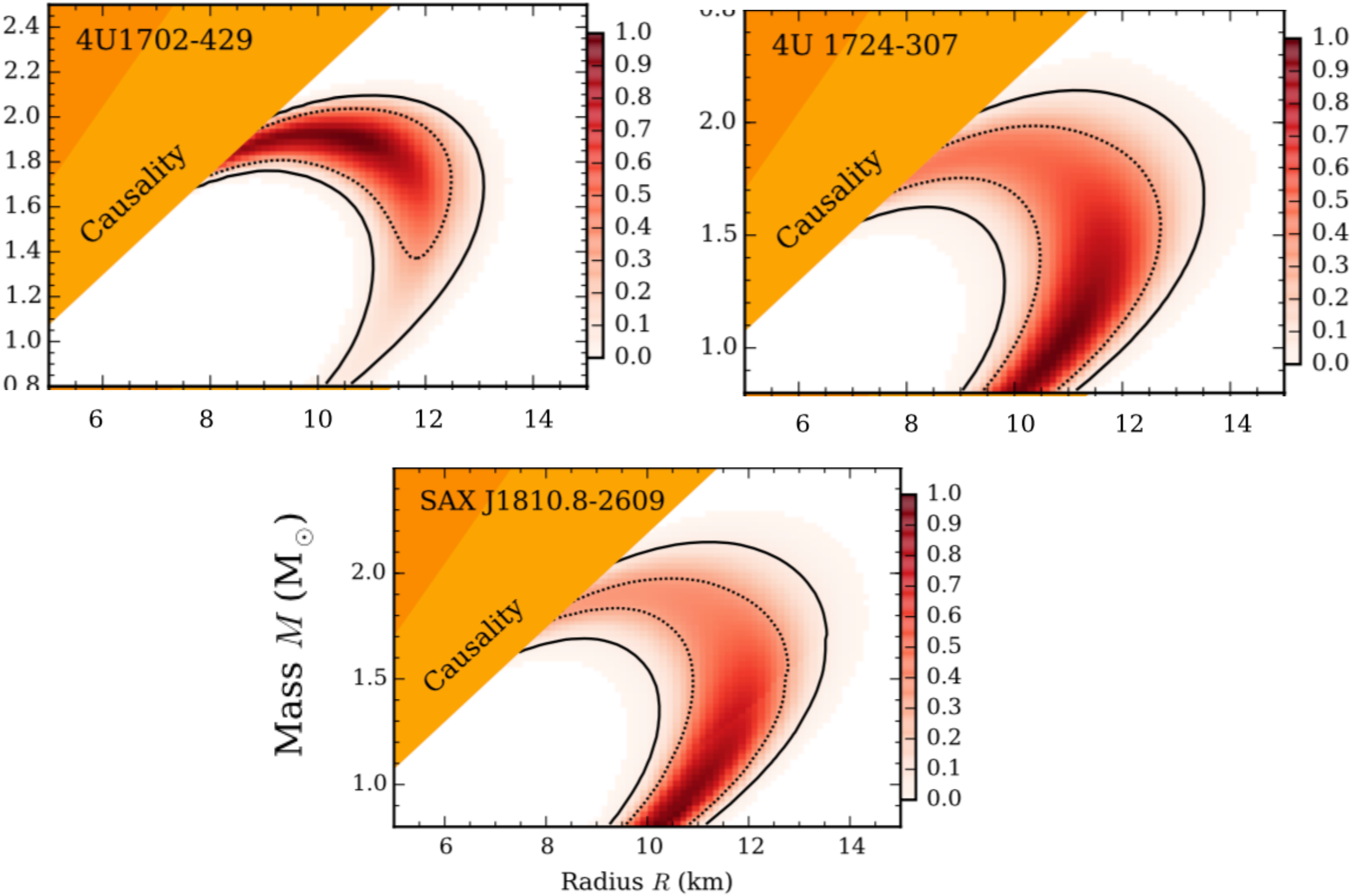
Spectra are nearly diluted blackbodies with color correction

$f_c = T_c / T_{eff} = 1.8$

M-R constraints from hard state bursts

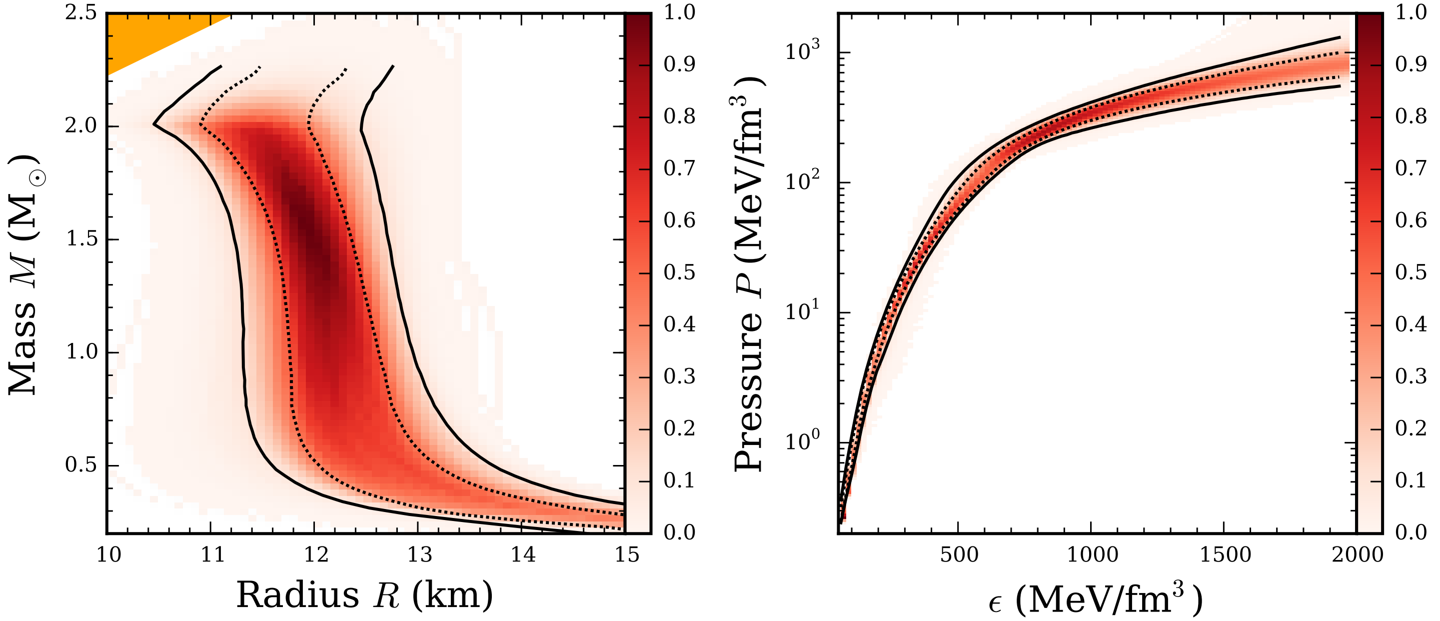


M-R constraints from hard state bursts

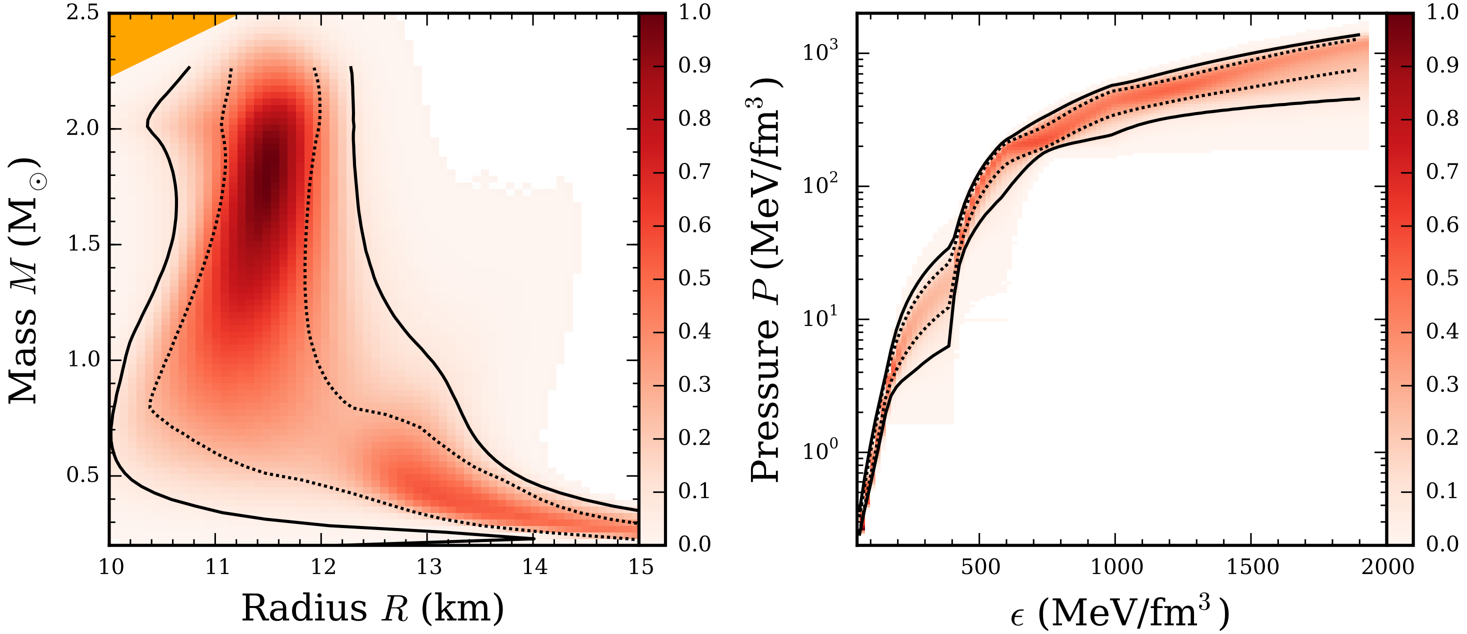


Parameterized EoS from the data

QMC + Model A



QMC + Model C



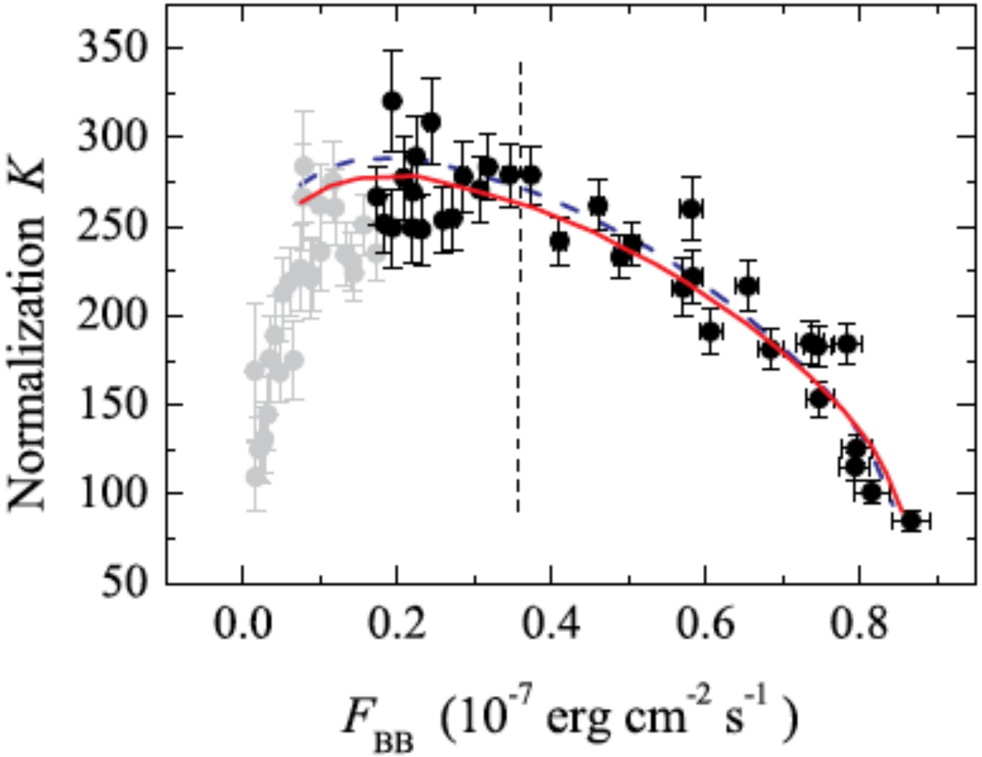
Bolometric correction to the cooling tail method

At the NS surface

$$\mathcal{F}_{\rm E} \approx w\pi B_{\rm E}(f_{\rm c}T_{\rm eff})$$

$$F_\infty = (w f_{\rm c}^4)^{-1}\, F_{\rm BB}$$

Observed



$$K = w\,\frac{R_\infty^2}{D^2}$$

fit directly in $M - R$ plane

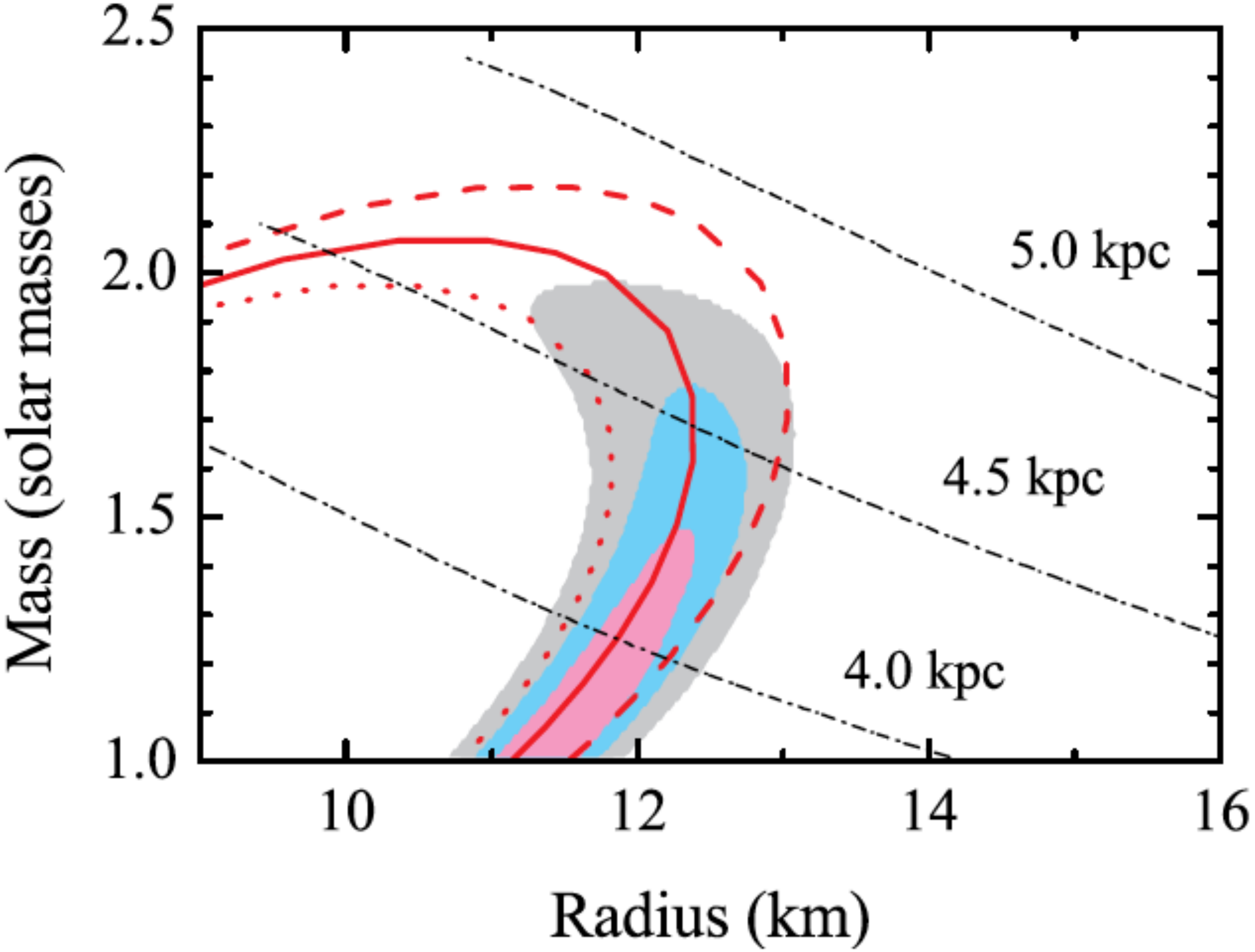
$K - F_{\rm BB}$

by

$$w - w f_{\rm c}^4\,\frac{F_\infty}{F_{\rm Edd}}$$

with D as a fitting parameter

M-R constraints for SAX J1810.8-2609



Conclusions

1. X-ray (thermonuclear) bursts with photospheric radius expansion are excellent tools to constrain M-R.
2. We have developed detailed atmosphere models to predict the spectral evolution of the X-ray bursts during cooling tails.
3. Spectral evolution of the "hard/low state" bursts is well described by the theory, while "soft/high state" bursts are not (and therefore they should not be used for M-R determination).
4. Current burst data (combined with existence of $2M_\odot$ NS) are consistent with the NS radii $11<R<13$ km,
5. There is still some systematic uncertainties related to the data selection (flux intervals), assumption about chemical composition, accounting for rapid rotation, etc.